CKM SCRF Cavity

Microphonics Detuning Compensation and Thermometry Developments

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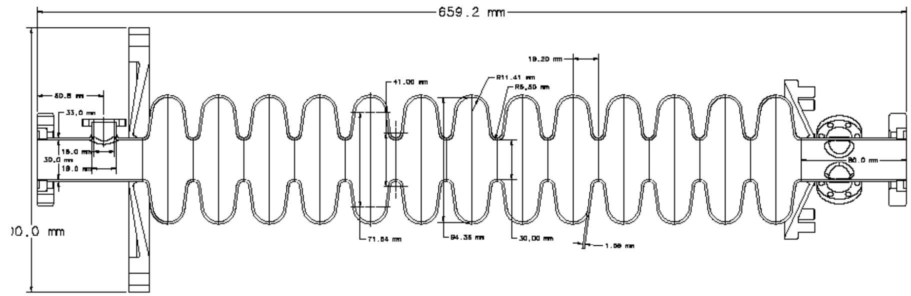
References

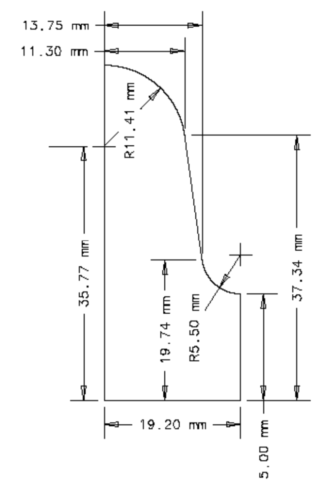
- **Piezo Tuner**
  - L. Lilje, S. Simrock, D. Kostin, “Characteristics of a Fast Piezo-Tuning Mechanism for Superconducting Cavities,” EPAC 2002, Paris, France.
  - M. Liepe, W. Moeller, S. Simrock, “Dynamic Lorentz Force Compensation with a Fast Piezotuner,” PAC 2001, Chicago.
- **Thermometry**
  - J. Knobloch, H. Muller, H. Padamsee, “Design of a High-Speed, High-Resolution Thermometry System for 1.5 GHz Superconducting Radio-Frequency Cavities,” Review of Scientific Instruments 65(11), 1994.
  - T. Junquera, A. Caruette, M. Fouaidy, Q. Shu, “Surface Scanning Thermometers for Diagnosing the Tesla SRF Cavities,” PAC 1995

Some CKM SCRF Cavity Parameters

- Frequency: 3.9 GHz
- Cells/cavity: 13
- Cavity Length: 660 mm
- $Q_{ext} = 6 \times 10^7$
- Bandwidth (f/ Q_{ext}): 65 Hz

- Main Injector Cycle Time: 3 sec
- Extracted Beam Duration per cycle: 1 sec





Detuning Tolerance Target

- To keep RF power requirements low, it is desirable to keep the resonance frequency within ~ 1/10th of the bandwidth:

$$\frac{P_{comp}}{P_{(\Delta f=0)}} = \frac{1}{4}\left[\frac{\Delta f}{f_{1/2}}\right]^2 \qquad f = 3.9\ GHz \pm 6.5\ Hz$$

- From Finite Element Analysis models, ± 6.5 Hz corresponds to ± 3.1 nm in a 13-cell CKM cavity length.
- Failure to achieve this detuning tolerance target would require de-Qing the cavity further to increase its bandwidth, thus increasing the RF power cost.

Detuning Contributions

- Lorentz Force Detuning
  - The rf magnetic field in a cavity interacts with the rf wall current resulting in a Lorentz force which can cause a small deformation of the cavity shape resulting in a shift of the cavity resonant frequency.
  - Important at high fields and for a pulsed accelerator such as TESLA.
- Microphonics Detuning
  - Thin-walled, narrow-bandwidth superconducting cavities are sensitive to mechanical vibrations in the acoustic range from pumps, compressors, etc.

Detuning Compensation

- Microphonics detuning is the main concern for CKM cavities. Lorentz force detuning is less of a concern because of the relatively long OFF (2 sec), long ON (1 sec) operating cycle. It is more of a concern for pulsed cavities such as TESLA (950 μs flattop, 5 to 10 Hz repetition rate).
- The stepping motor used for fine cavity tuning cannot respond fast enough for active microphonics detuning compensation.
- A fast Piezo Actuator has been demonstrated to be a good candidate for dynamic Lorentz force detuning compensation. This application relies on the high repetitive characteristics of this type of detuning.
- We are investigating using a Piezo Actuator for random microphonics detuning compensation.

Piezo Actuator

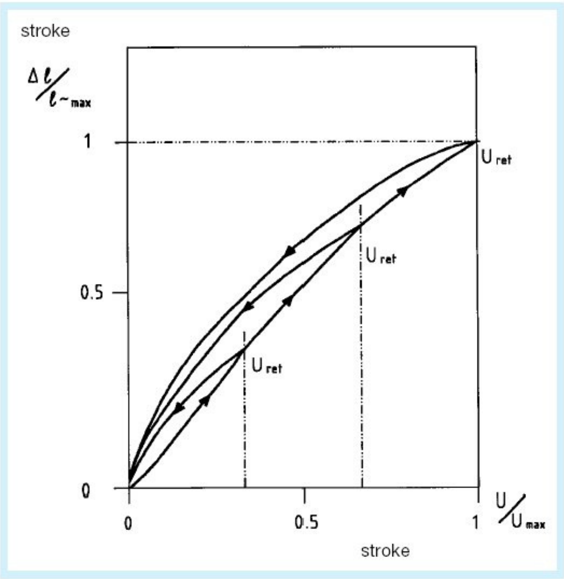


Fig.5:
Displacement/voltage diagram of a typical piezostack for different voltage levels (within U_{max}). U_{ret} returnpoint of voltage for the individual cycle.

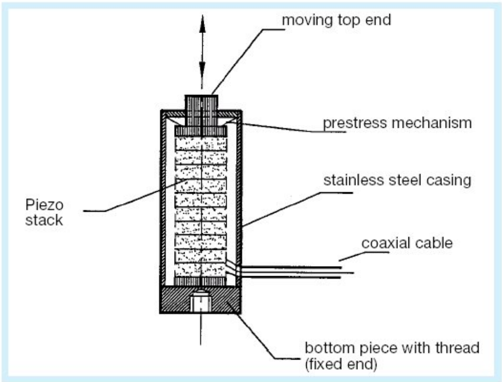


Fig. 3a:
Piezoactuator with casing with internal mechanical prestress

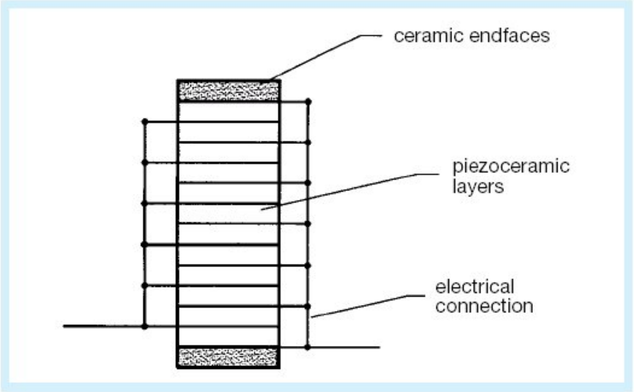
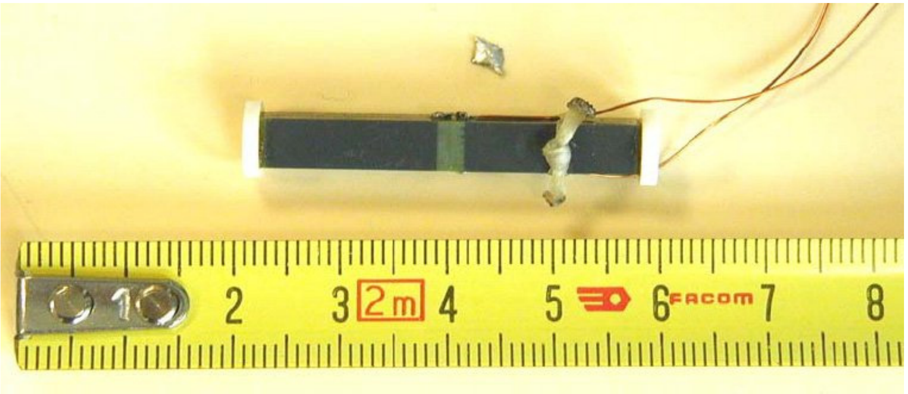


Fig. 1
Principle design of a piezostack actuator



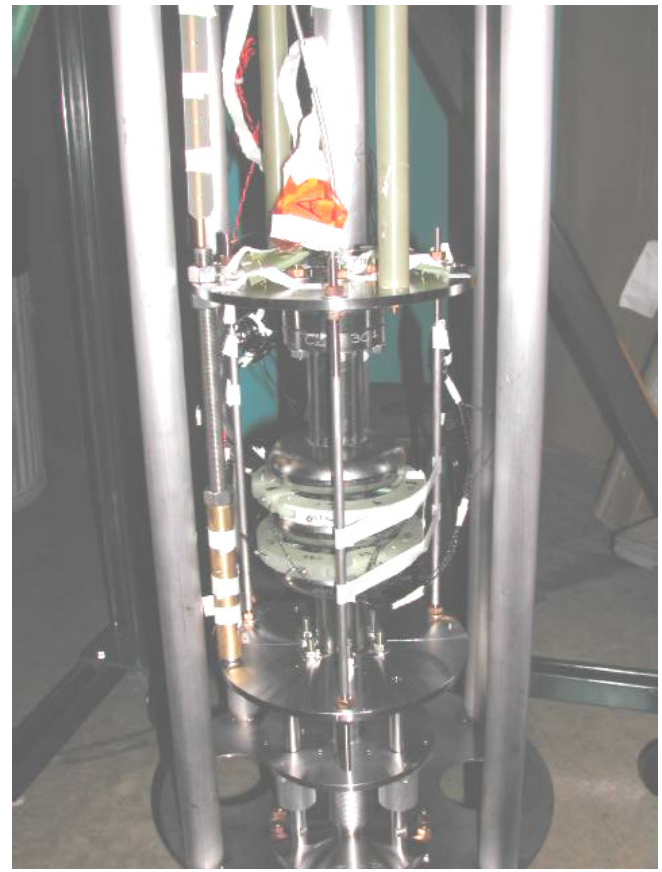
Piezo Actuators

Piezo Actuator Selection

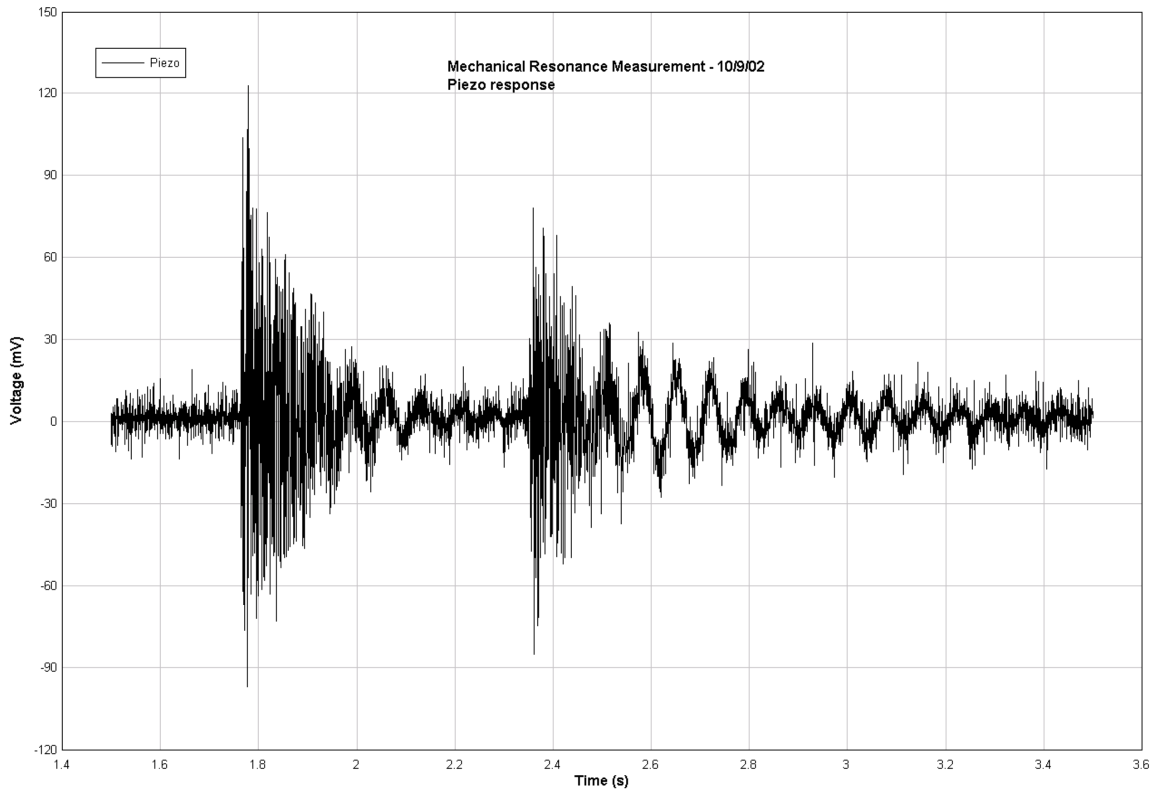
- For prototype studies, we selected the Piezo Actuator P-206-40 from Piezosystem Jena. Some of its parameters are:
  - Bare piezostack compatible with cryogenic operation in liquid helium.
  - Voltage range: -10V to 150V
  - Range of motion (room temperature): 80 µm. At 1.8 K: ~ 8 to 10 µm
  - Length: 90 mm
  - Stiffness: 12 N/µm
  - Maximum Load: 1000 N
  - Capacitance: 8500 nF

3-cell prototype instrumentation

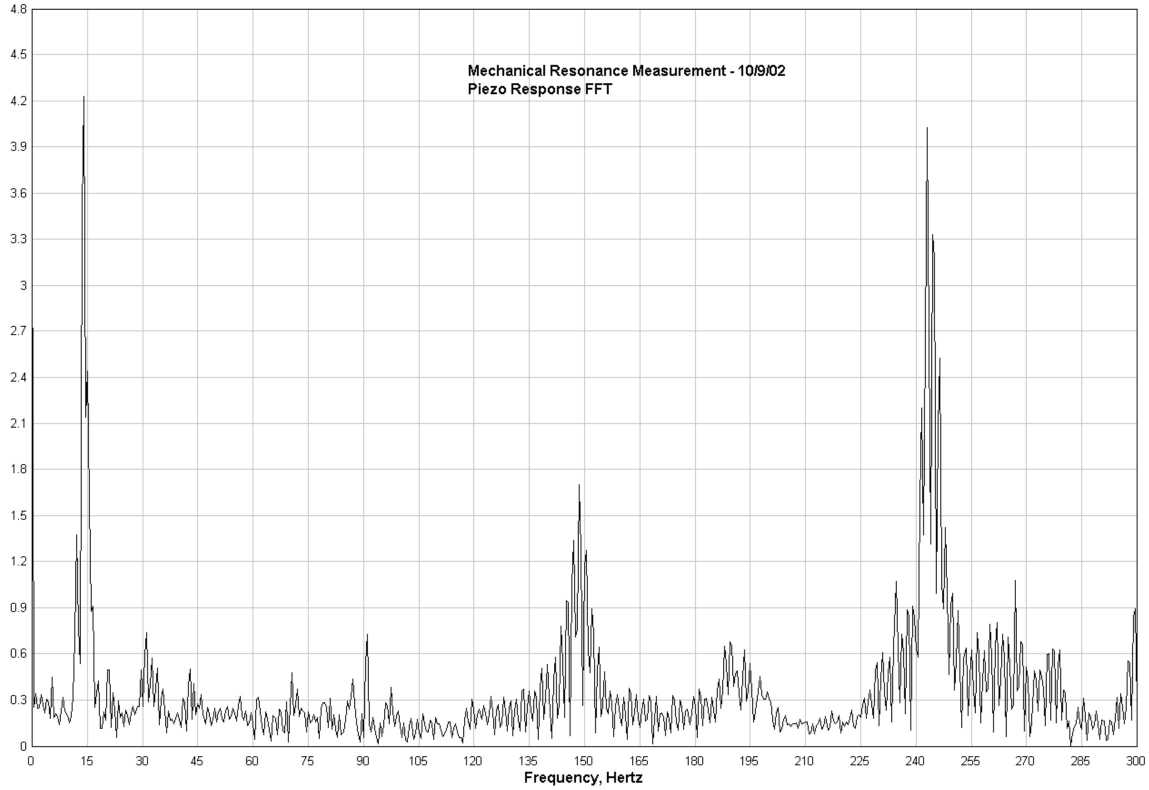
- 3-cell prototype showing location of piezo element plus thermometry rings.
- Piezo element was used both as a sensor and as an actuator.



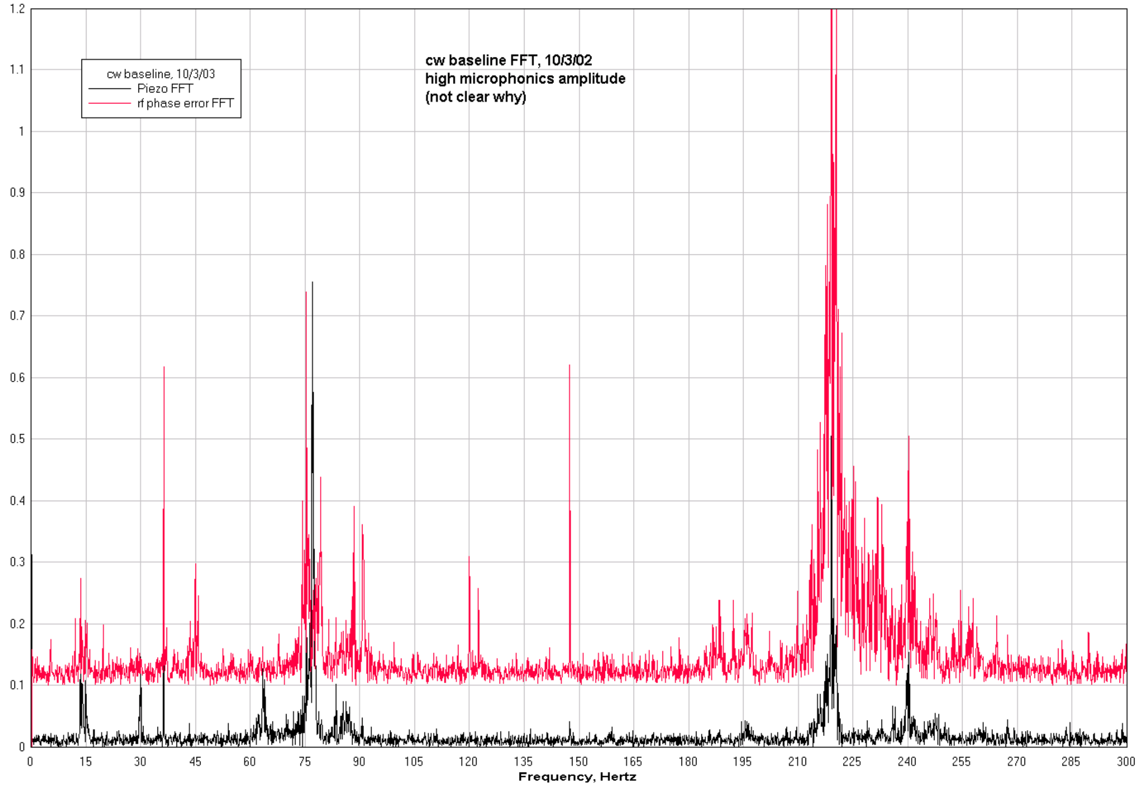
3-cell Mechanical Resonance



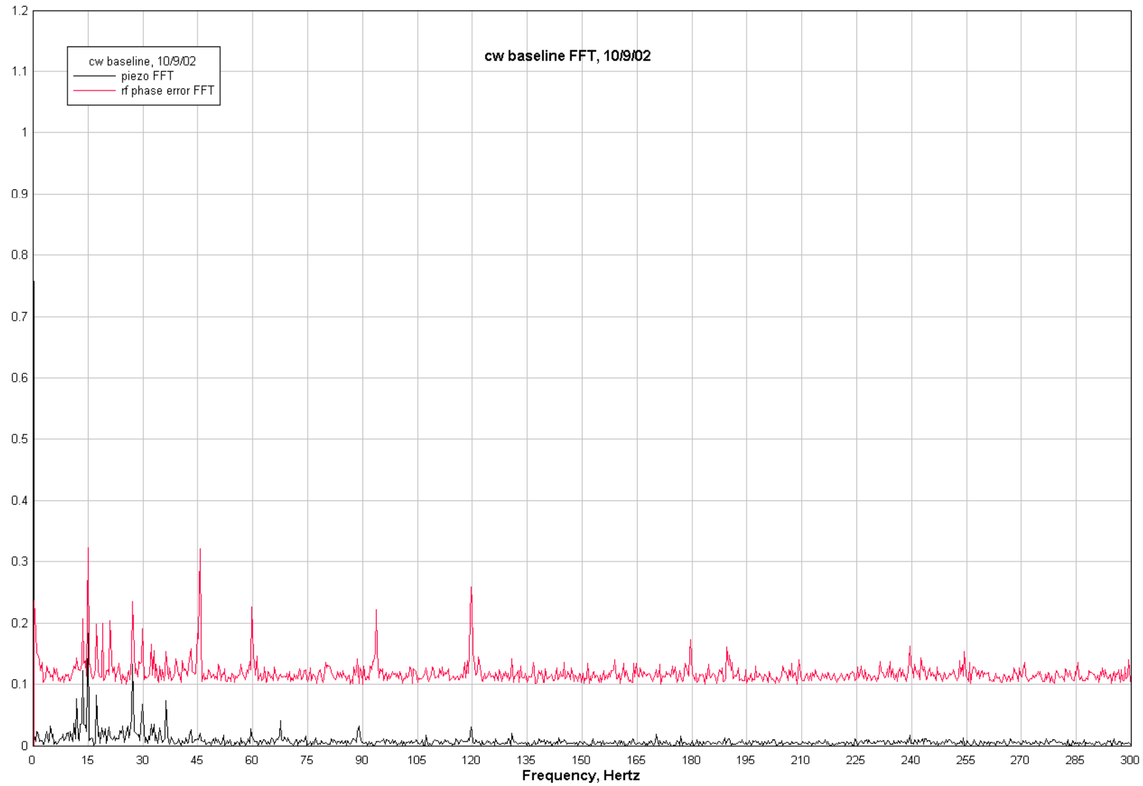
3-cell Mechanical Resonance FFT



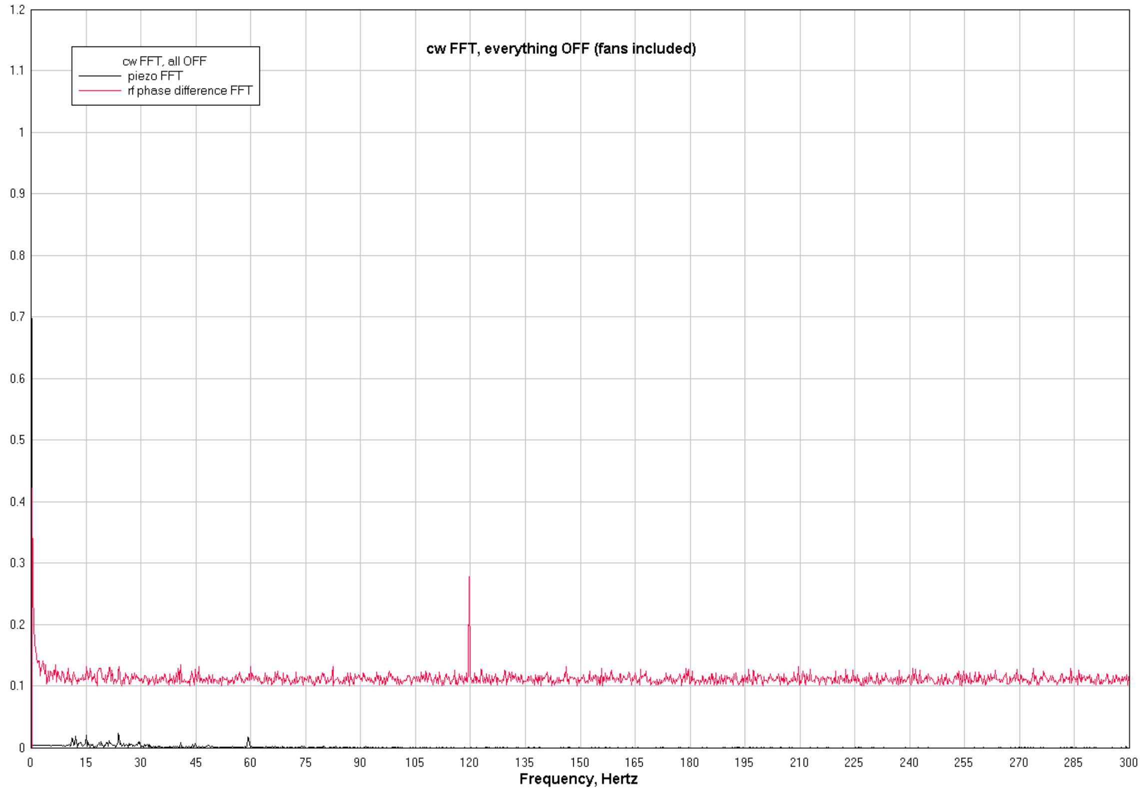
Microphonics FFT - High Amplitude (~ ± 550 Hz)



Microphonics FFT – Low Amplitude (~ ± 100 Hz)

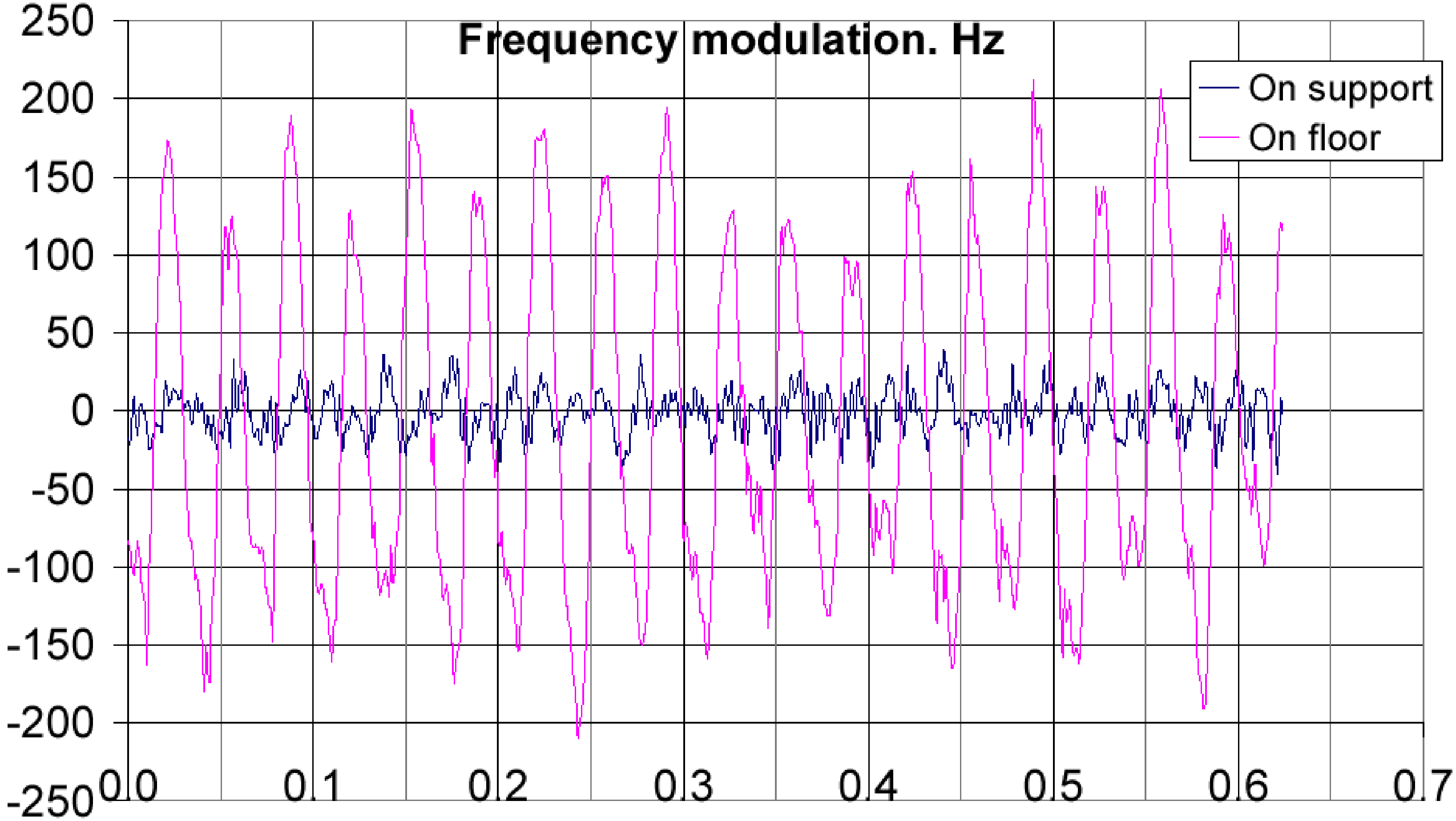


Microphonics FFT – All Pumps OFF

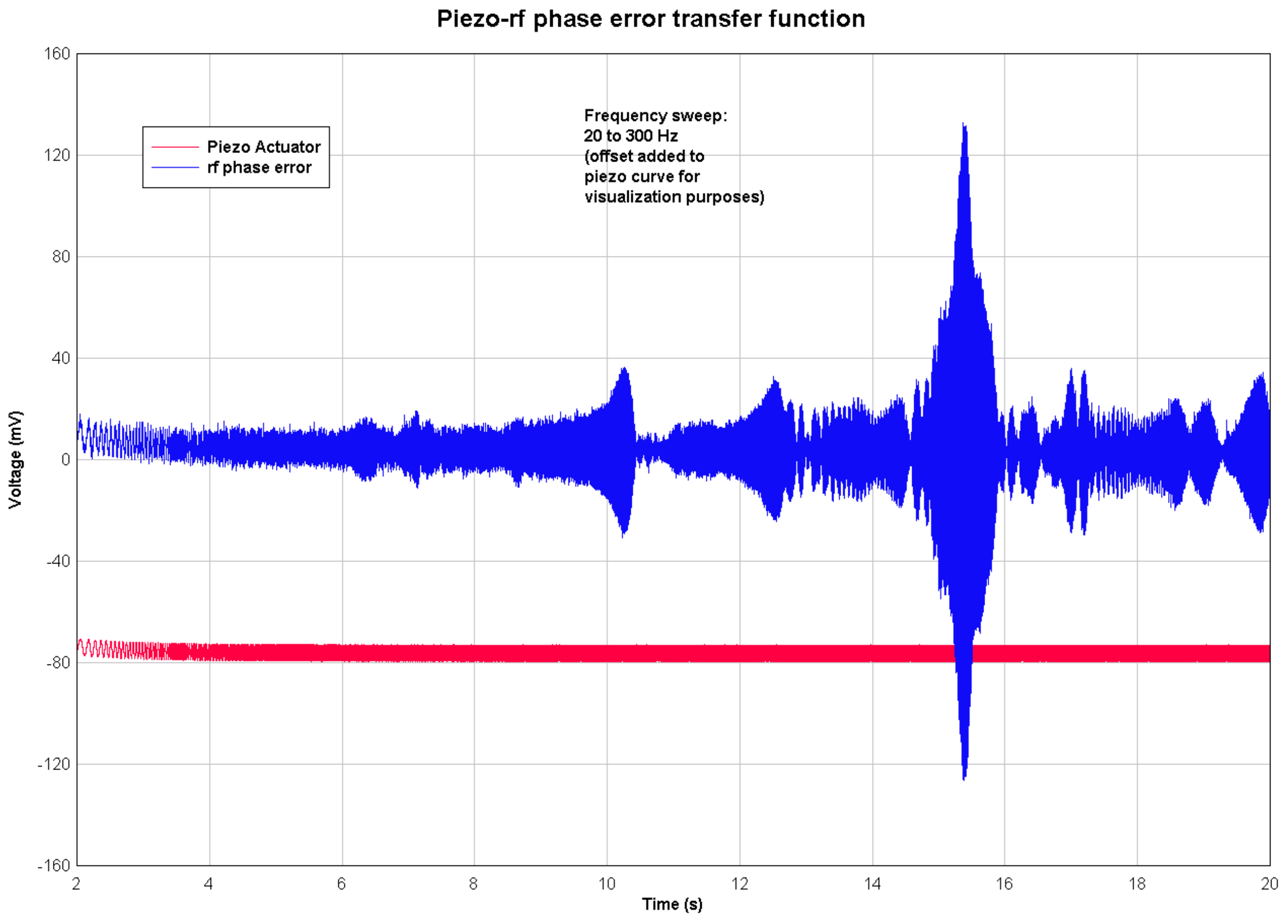


Microphonics – Dewar Support Modifications

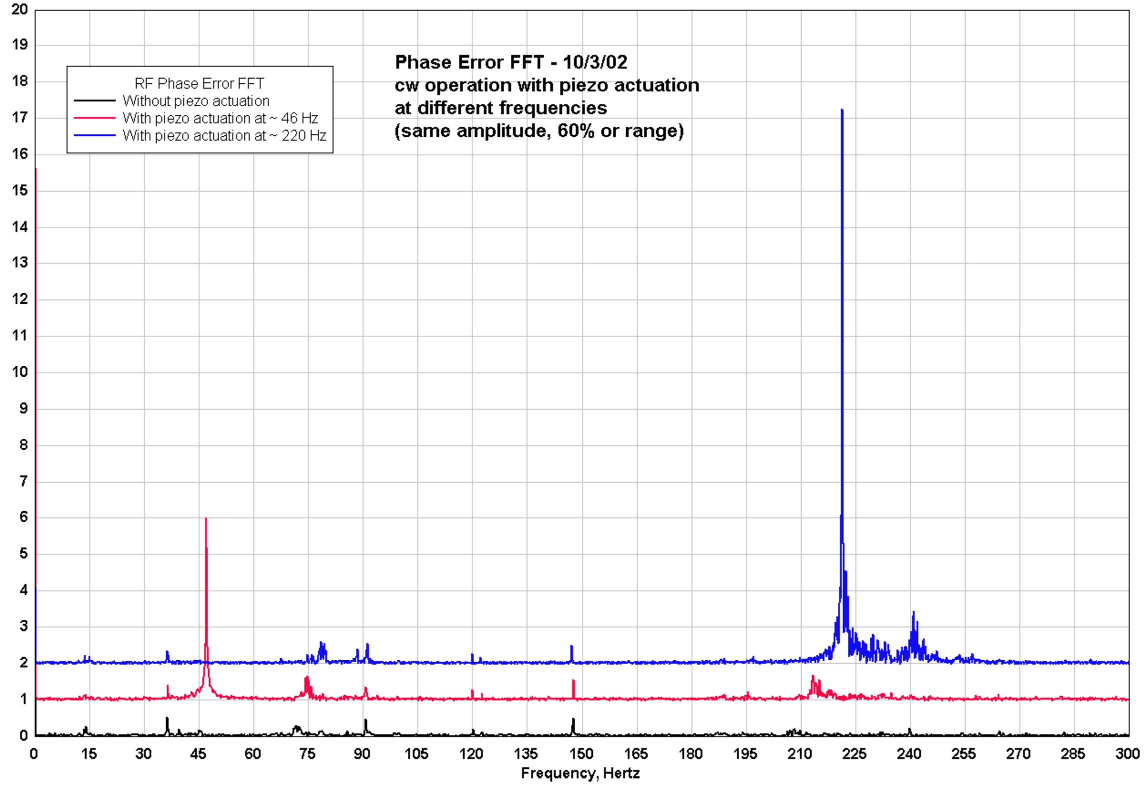
(Measurements by T. Khabiboulline, April 2003)



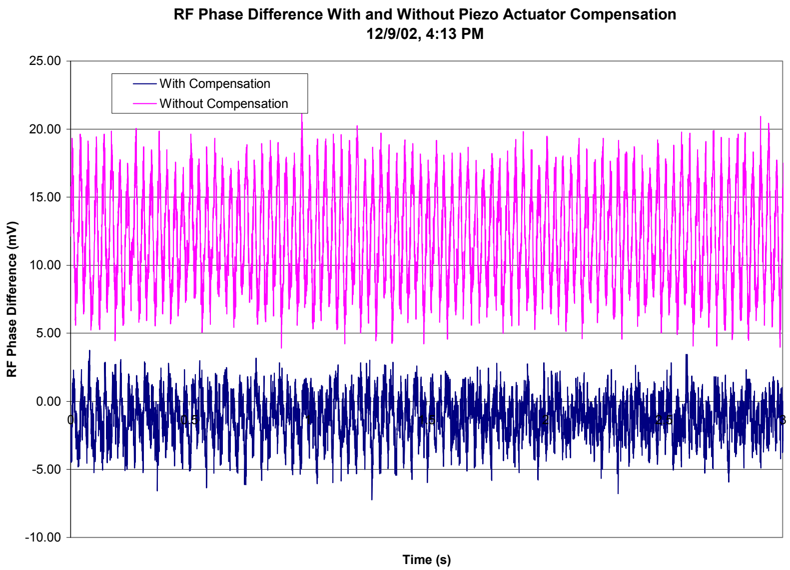
Piezo-RF Phase Error Transfer Function

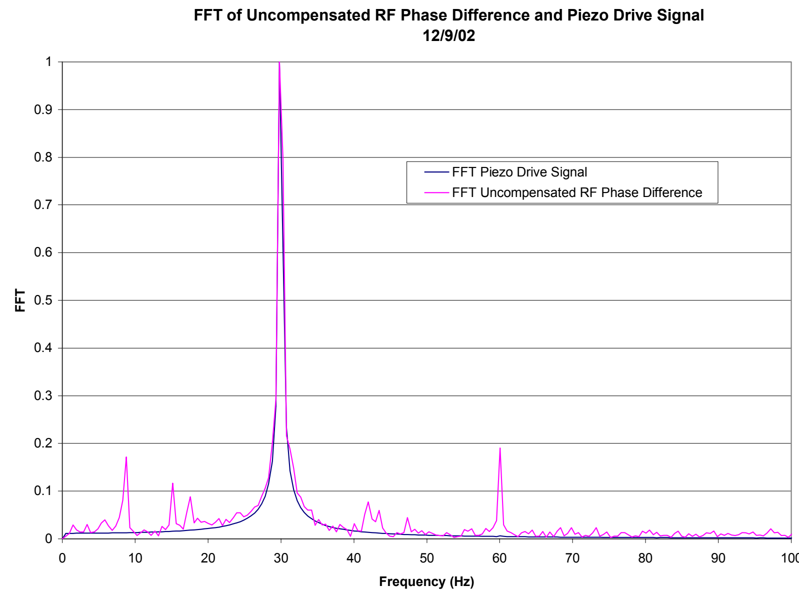


RF Phase Error With Piezo Actuation



Manual Detuning Compensation

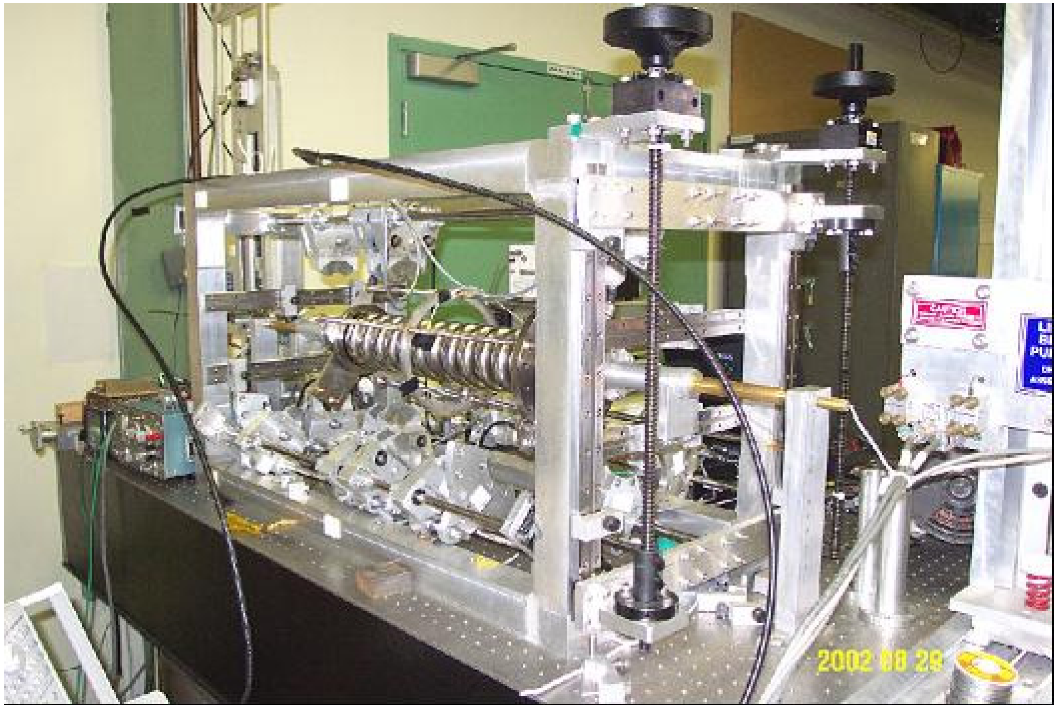




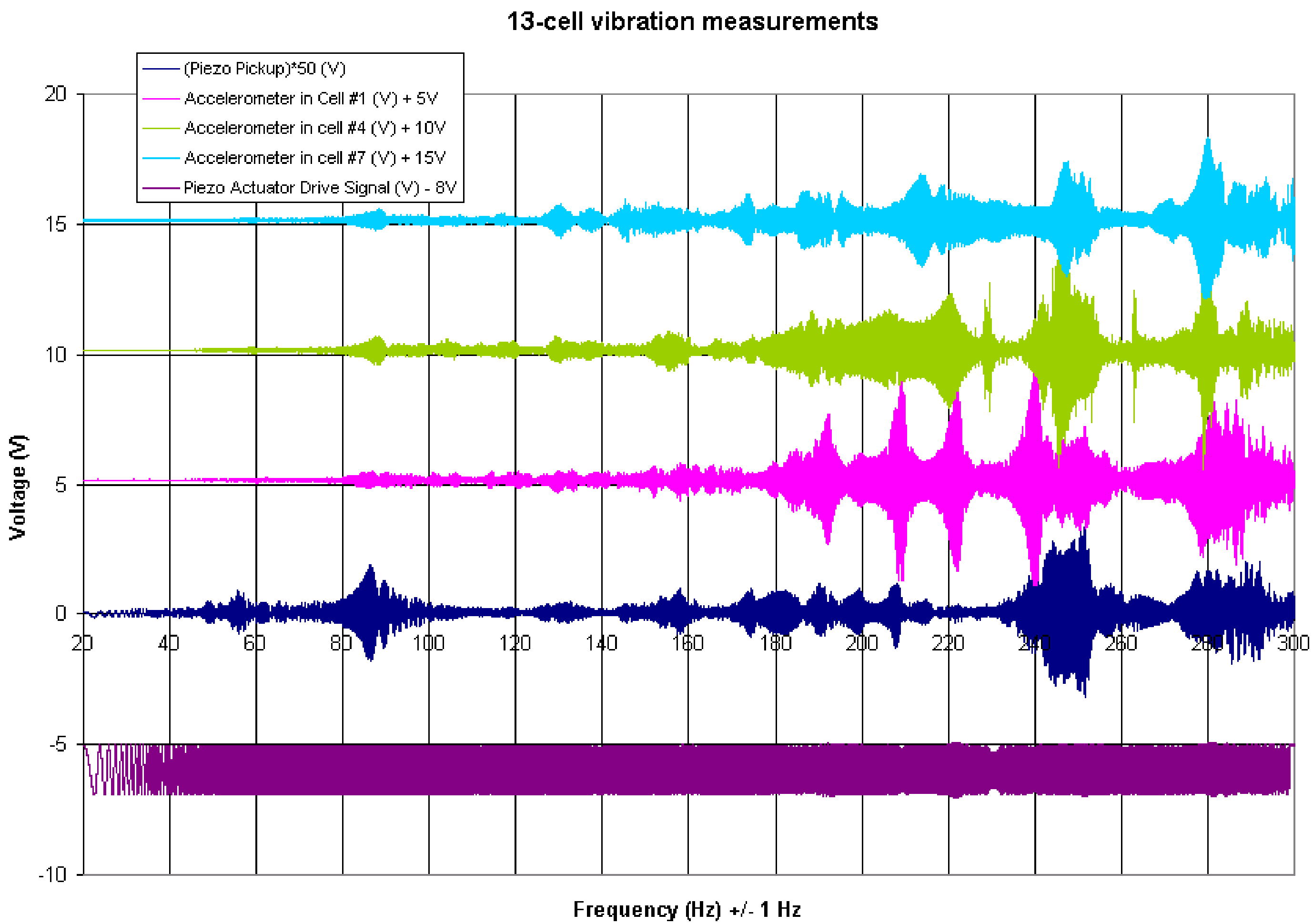
Microphonics detuning was reduced from ± 375 Hz to ± 175 Hz. Manual compensation is difficult because frequency, amplitude, and phase must be adjusted. In addition, only one sine frequency was used to drive the piezo actuator.

13-cell Vibration Measurements

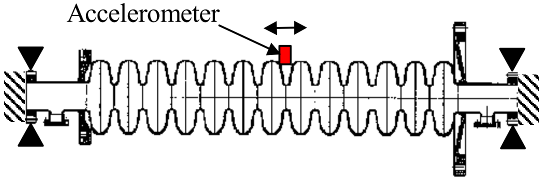
- Piezo Actuator and Piezo Sensor at each end.
- Accelerometer at cells #1, #4, and #7.
- Frequency sweep: 20 Hz to 300 Hz in 20 seconds.

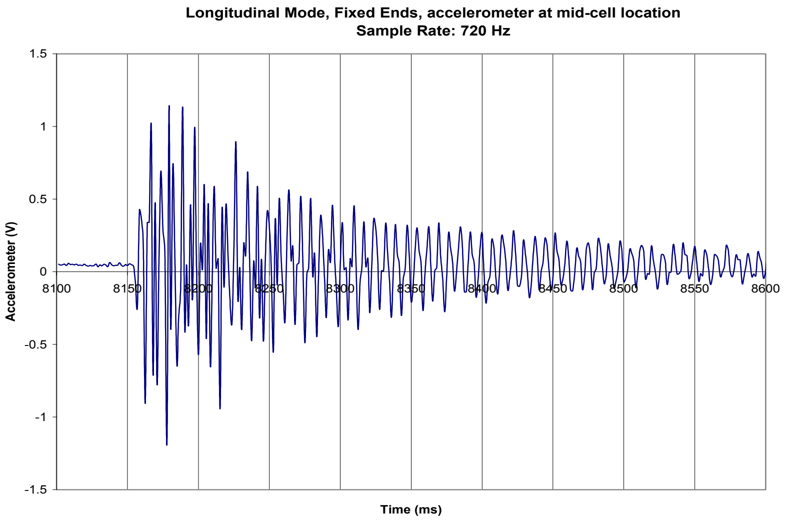


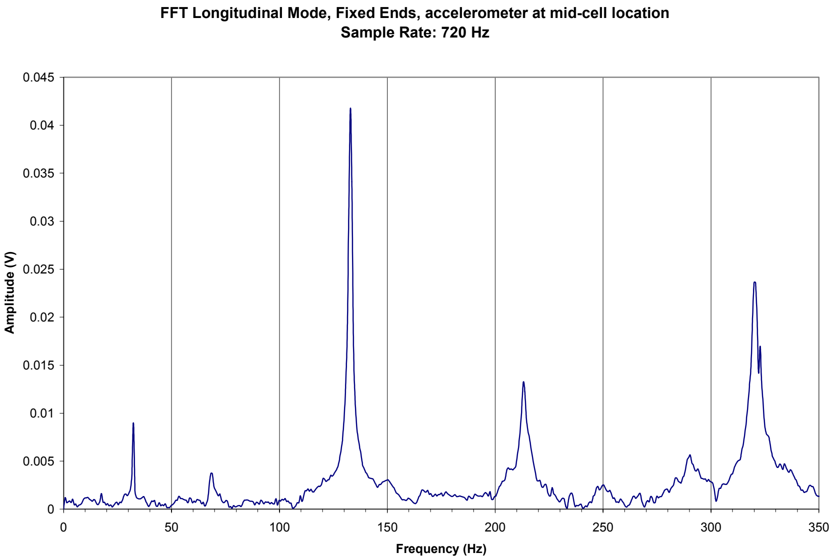
13-cell Vibration Measurements Results



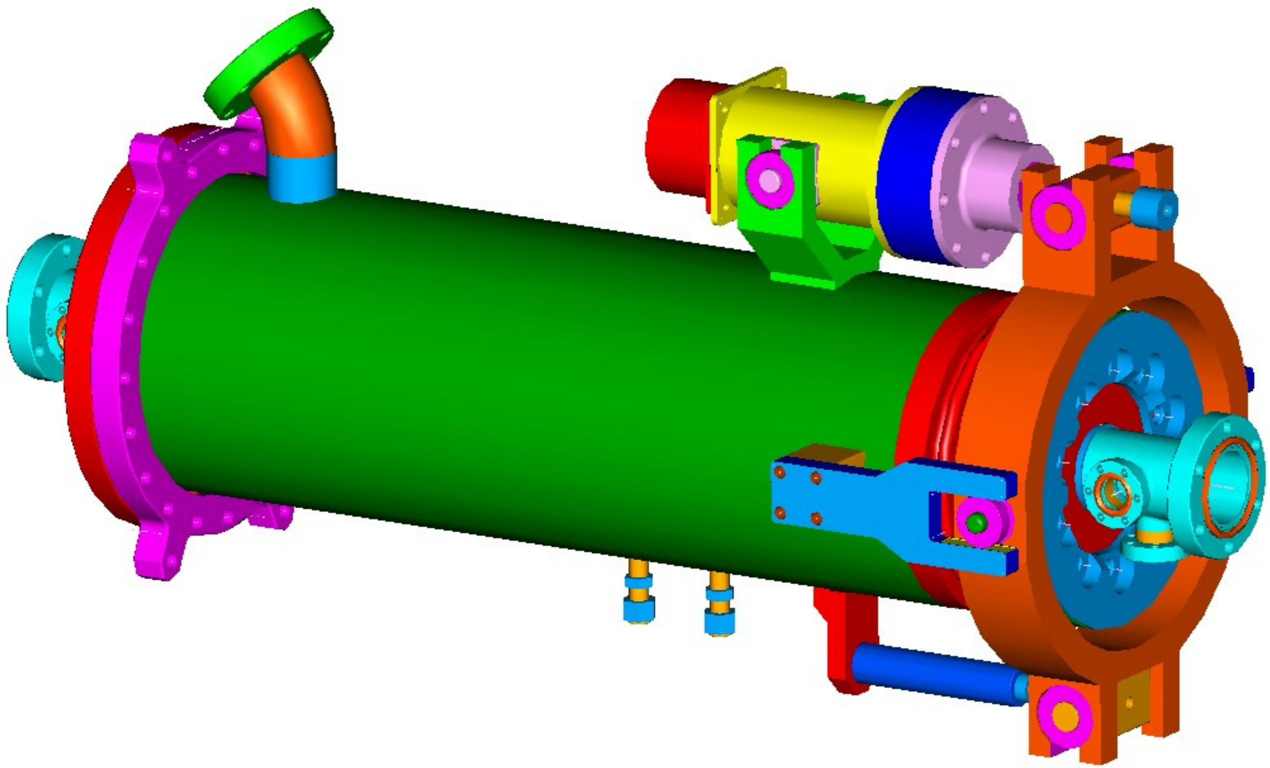
13-cell Mechanical Resonances



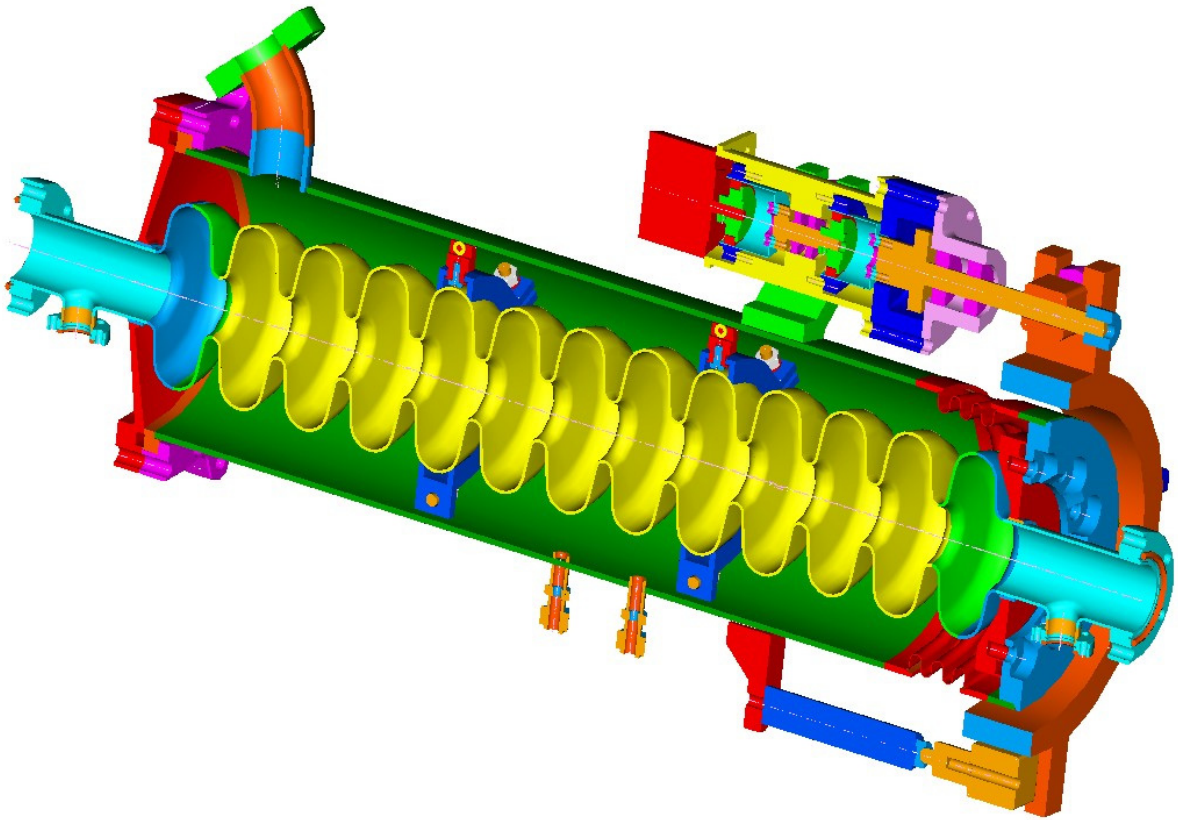




13-cell cavity tuner



13-cell cavity tuner cross section

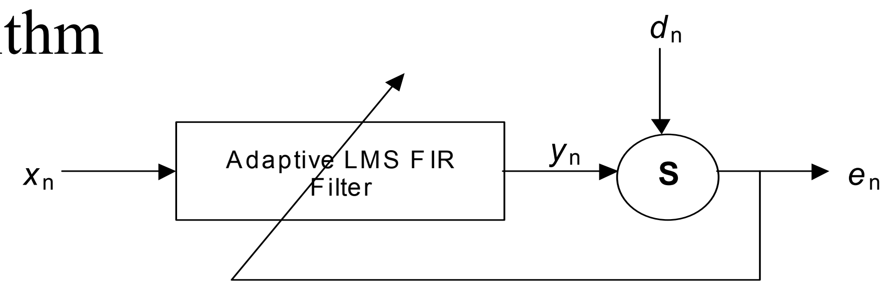


Piezo Tuner Control

- Transfer Function measurements show a large number of modes with a large phase shift of several hundred degrees over the frequency range of interest. This makes feedback for microphonics control using the RF signal not possible with the piezo actuator.
- We are investigating applying adaptive feedforward control with algorithms typically used for noise or vibration cancellation such as the LMS filter.
- The CKM cavity operating cycle (1 sec ON, 2 sec OFF) would make it possible for these types of algorithms to adapt to microphonics perturbations during the beam OFF phase.

Adaptive Feedforward Control

- LMS Algorithm



The output of the filter is:

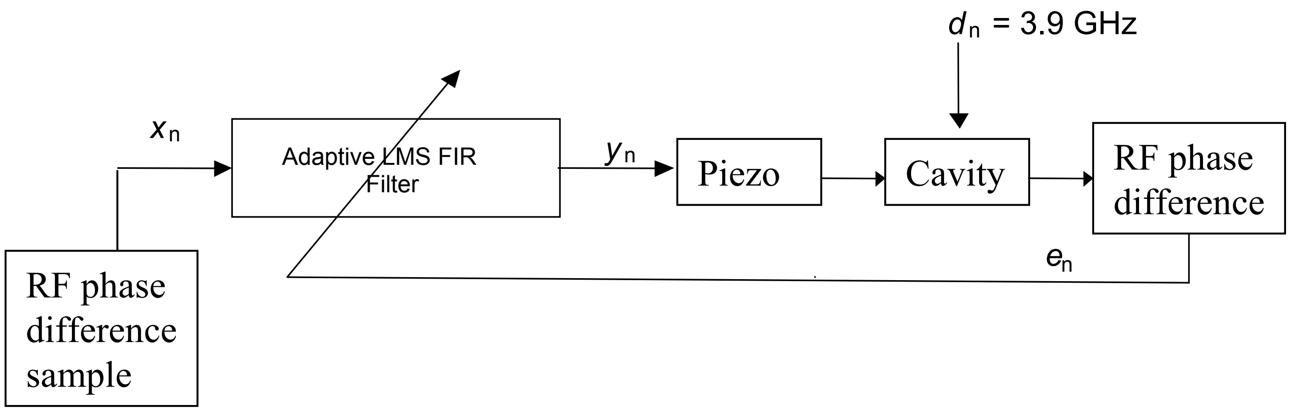
$$y(n)=w^T(n)\, x(n)$$

Where w*(n)* = [$w_0\ w_1 \ldots w_{M-1}$]^T is the *weight vector* at time index *n* and x*(n)* = [*x(n) x(n-1) … x(n-M+1)*]^T is the data vector of the *M* most recent input samples. The weight vector is adjusted each iteration according to equation:

$$w(n+1)=w(n) + 2u\, x(n)e(n)$$

Where u is a *convergence factor* the value of which affects the amount the weight vector is altered on each iteration.

LMS applied to CKM cavity (preliminary)

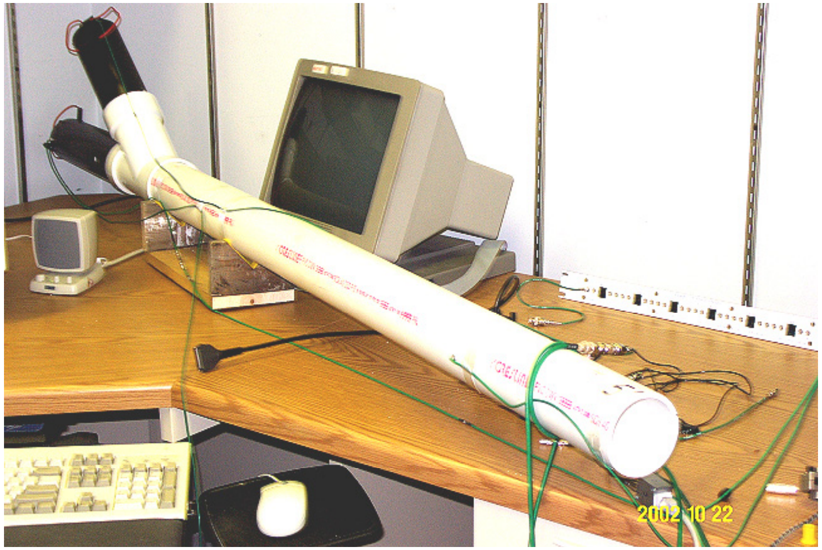


(taken while LMS is OFF and "replayed")

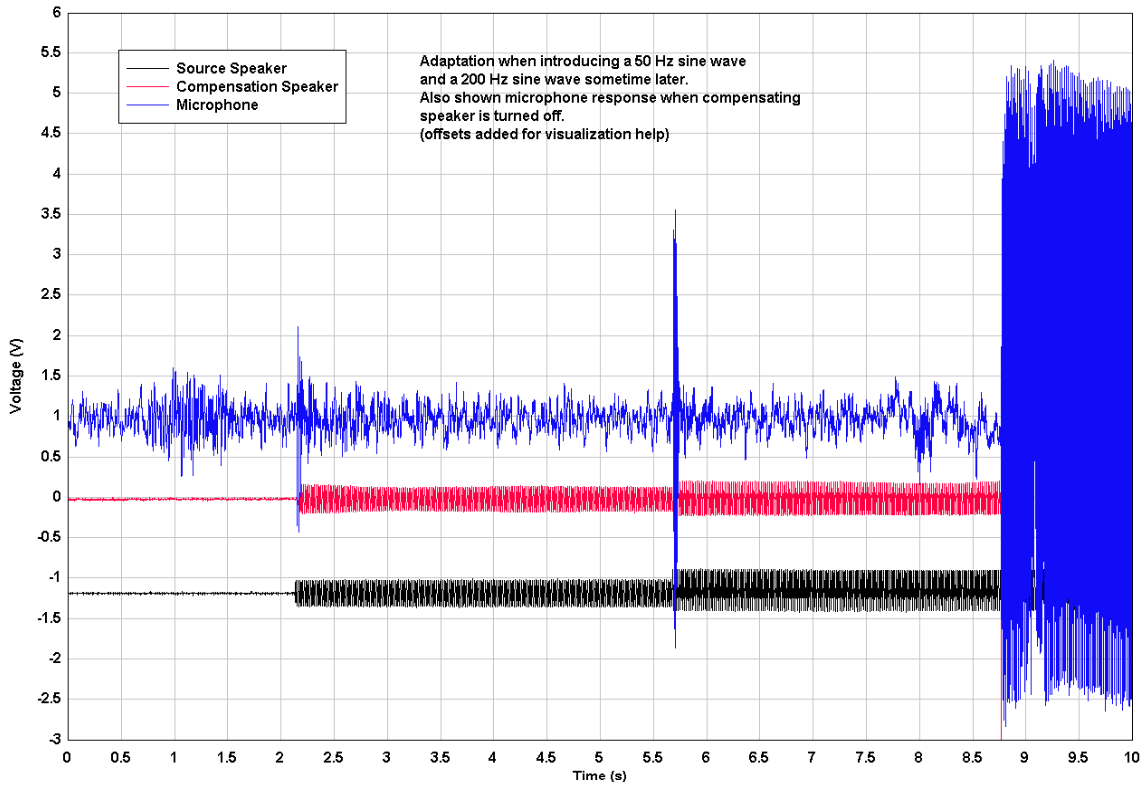
- This approach assumes the microphonics spectrum remains more or less constant between samples.
- Samples of the microphonics spectrum can be taken while the beam is OFF and then replayed to provide Xn. However, RF power is required for this measurement.

Active Noise Cancellation with Adaptive LMS Filter Concept Demonstration

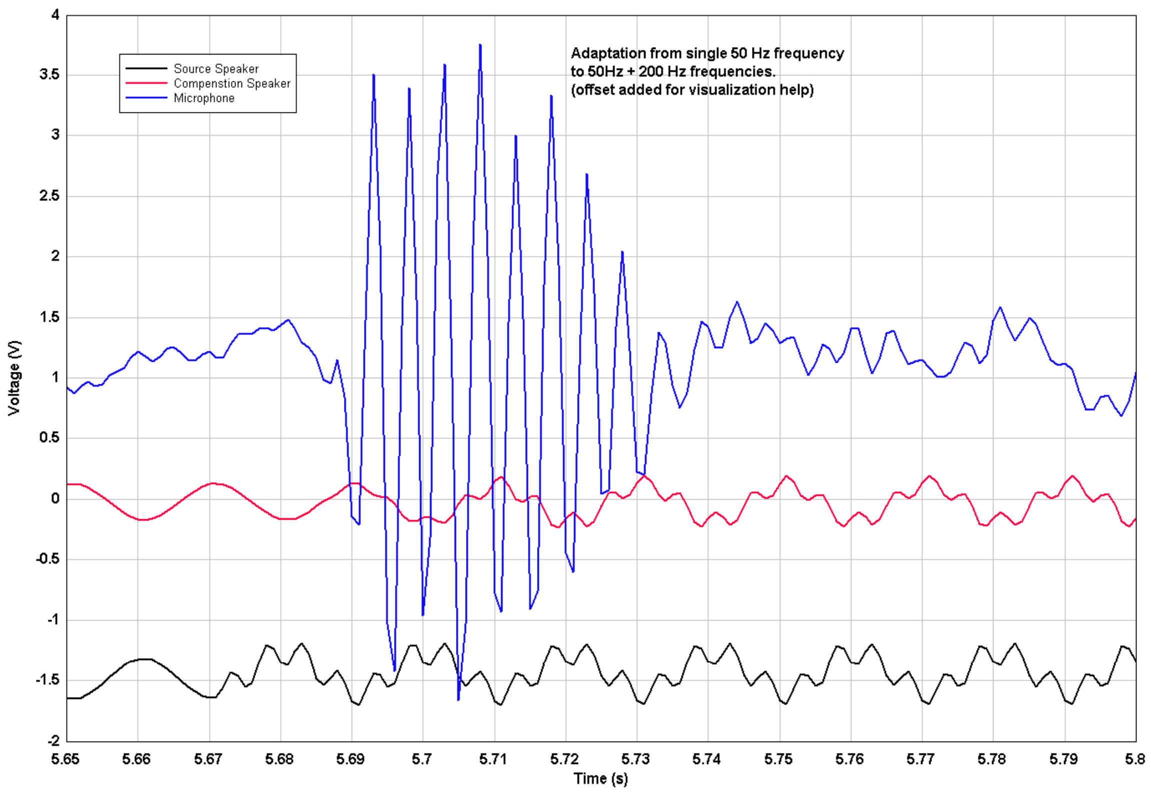
- The LMS filter was implemented to cancel noise from a source speaker in a duct using a compensating speaker.
- The algorithm was programmed in a real-time VxWorks operating system. The signals were acquired with a VME-based data acquisition hardware.



Noise Cancellation Results



Noise Cancellation Adaptation Details



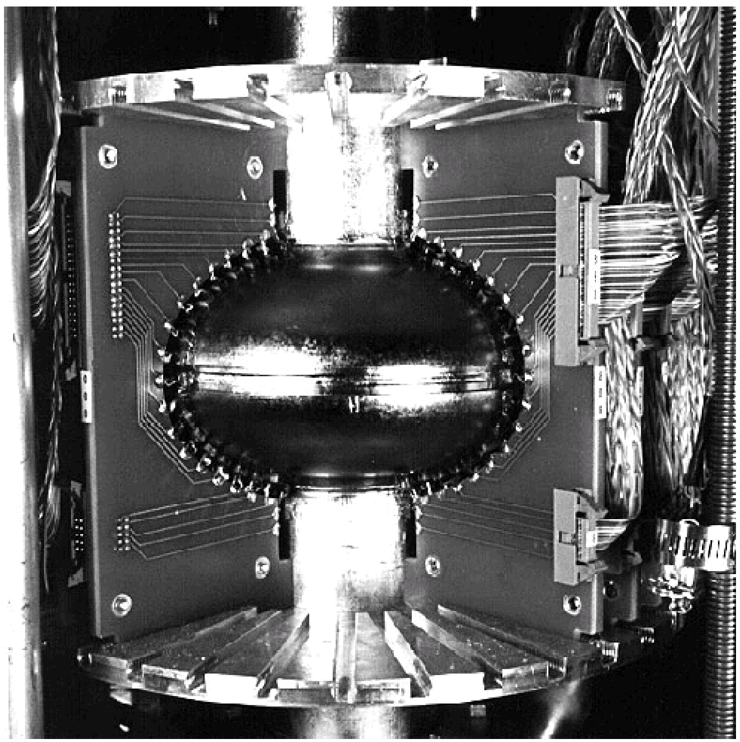
Path Forward

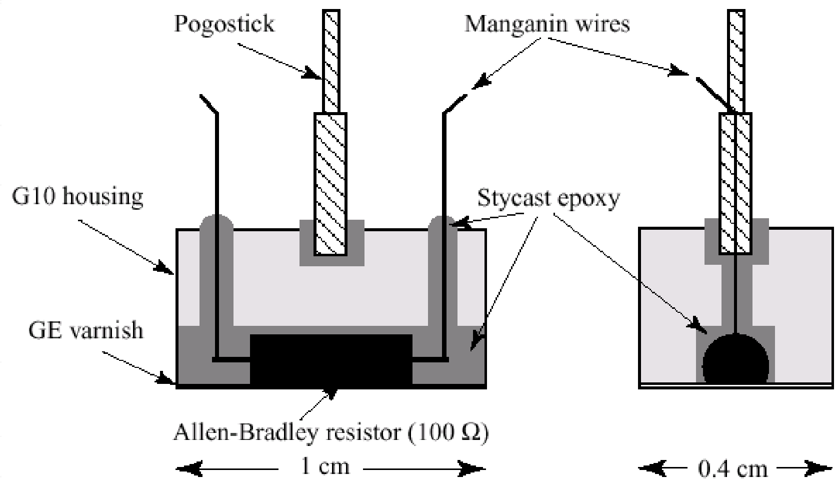
- Demonstrate automatic microphonics detuning compensation in the 3-cell prototype using an FPGA board programmed with the adaptive feedforward LMS algorithm.
- 13-cell cavity measurements in operating conditions (e.g., mechanical resonances, piezo-rf transfer function, uncompensated microphonics)
- Characterization of the high-load piezo actuator to be used in the 13-cell cavity.
- 13-cell cavity measurements automatic compensation: strategy, fine-tune algorithm, etc.
- Packaging for production.

Cavity Thermometry - General

- Cavity surface thermometry is used to study local distribution of various types of energy losses and identify defects.
- Main types of cavity loss mechanisms:
  - Thermal breakdown (related to surface magnetic field)
  - Field emission (related to surface electric field)
- The temperature sensing element is usually Allen-Bradley carbon resistors encased in epoxy to prevent excessive cooling of the thermometer by the helium bath.
- Fixed or rotating arrays of thermometers have been used.

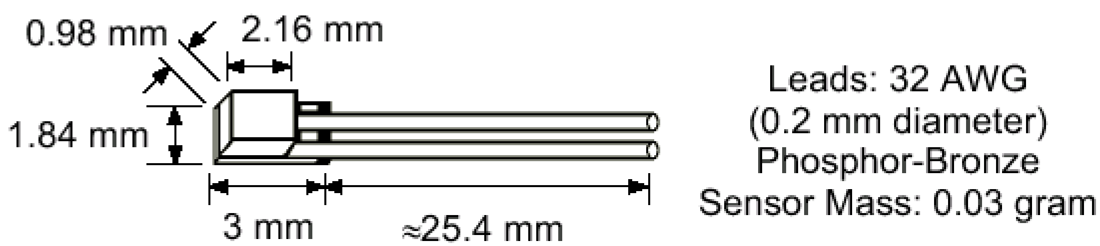
Example: 1.5 GHz Cavity (Cornell)





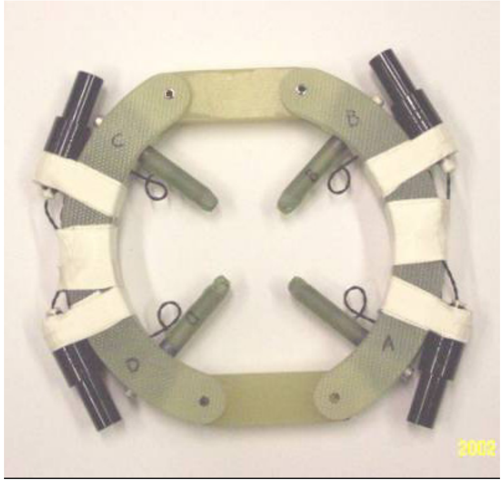
CKM Cavity Thermometry

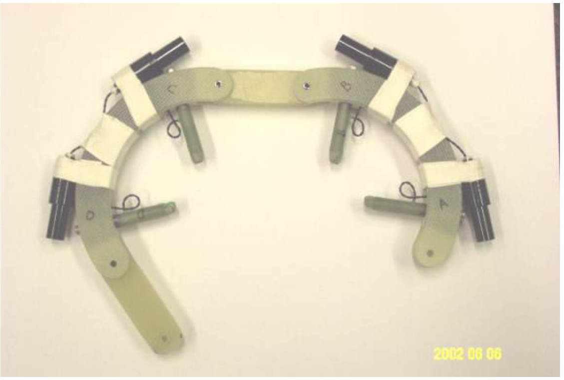
- Small Iris size (30 mm) makes it difficult to use the general approach used in other cavities with Allen-Bradley carbon sensors. A smaller CERNOX sensor was used instead.

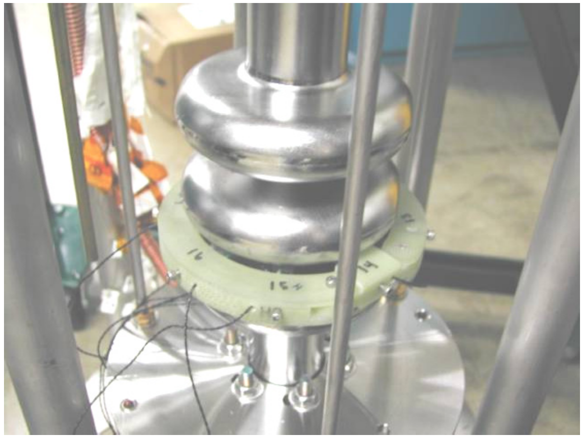


- The sensor was attached with epoxy to a spring-loaded G-10 stick, and an Indium half-sphere was glued to the tip of the CERNOX sensor and covered with Apiezon grease prior to installation to improve thermal contact.

CKM Cavity Thermometry

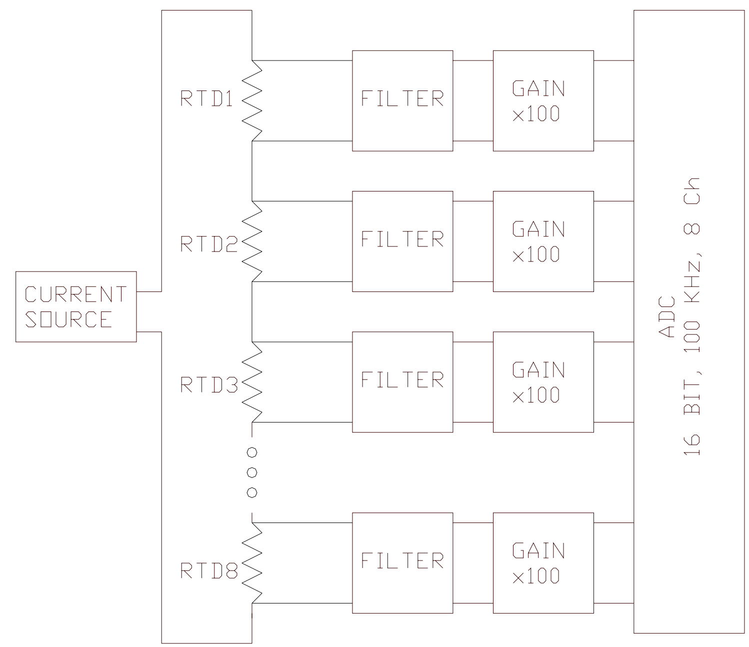






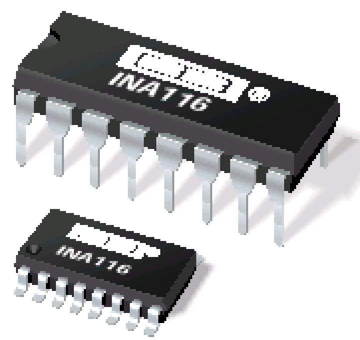
Thermometry DAQ System

- A fast (KHz) CERNOX readout system is required to capture surface T during cavity quench.
- Available systems (commercial or in-house) were too slow (a few samples per second)
- We designed a system based on a Keithley precision current source, an in-house amplifier designed for this application, and a 16-bit, 100 kHz ADC card.

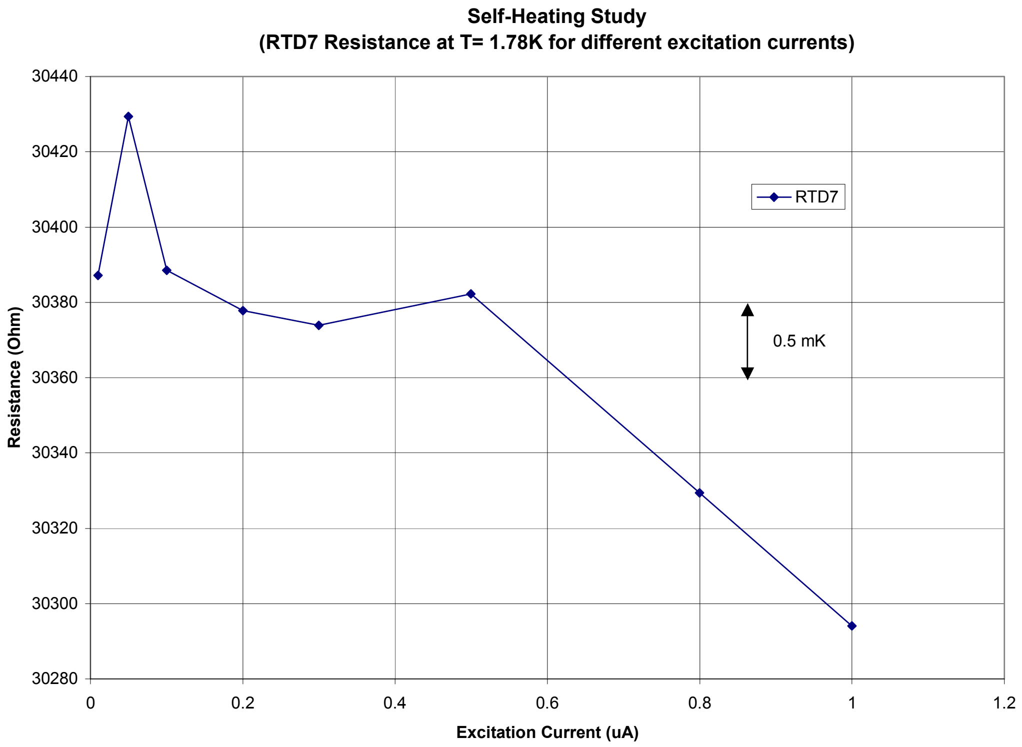


In-house amplifier

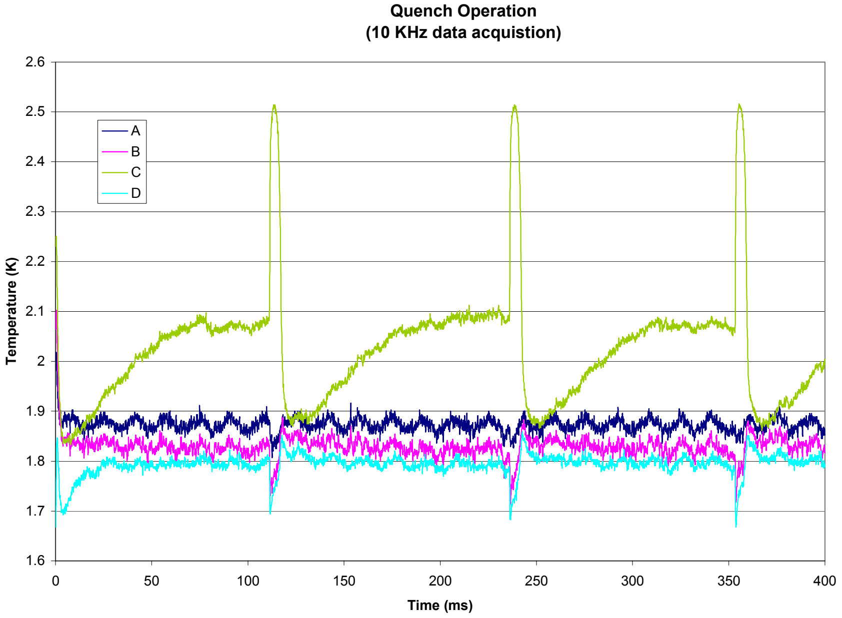
- To avoid self-heating, CERNOX RTDs must be driven with a very low current (< 0.5 uA).
- The resulting RTD voltage is typically a few mV. Filtering and amplification is needed before digitizing the signal.
- To avoid errors, an ultra low input bias current instrumentation amplifier (< 3 fA) such as the INA116 is required.

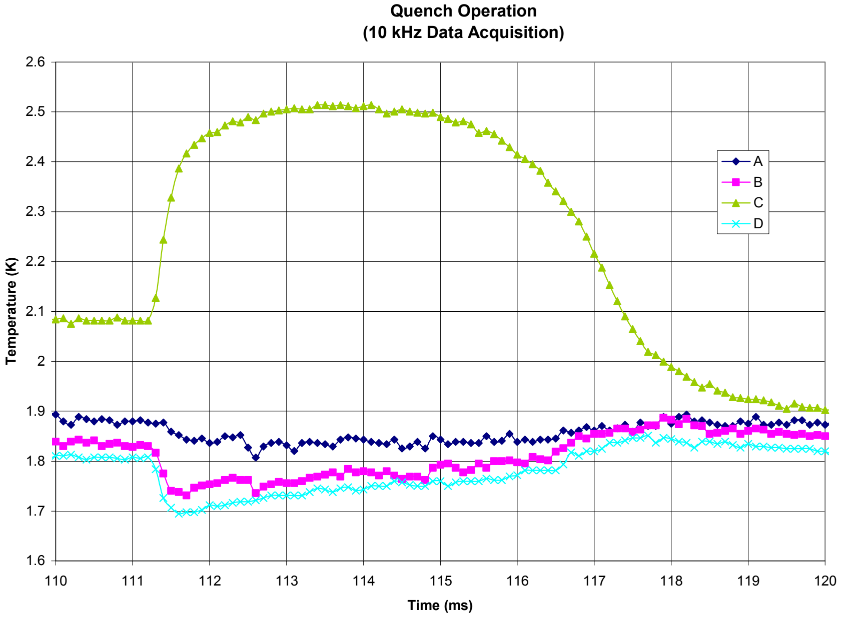


Self-Heating Study

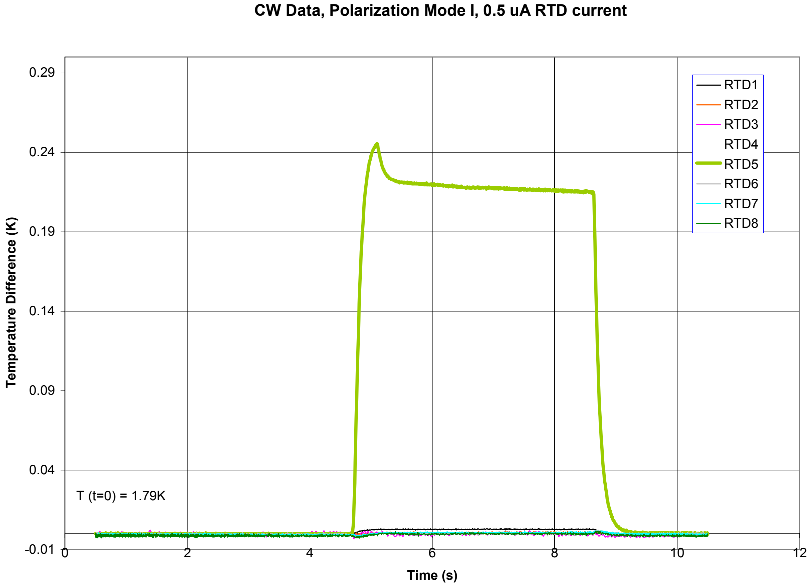


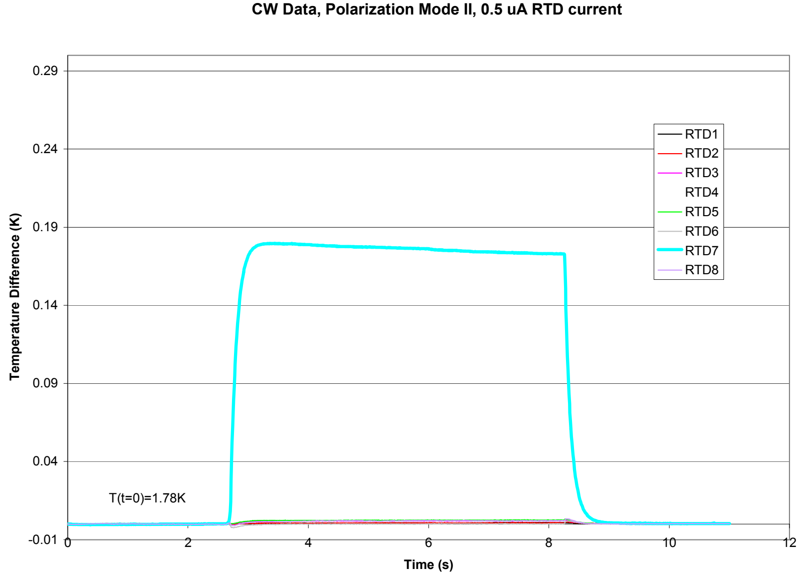
Cavity Quench Thermometry





Cavity cw thermometry at two different polarizations





Path Forward

- We need to scale up the thermometry system for the 13-cell cavity.
- Software for automatic data reduction and analysis has to be written.